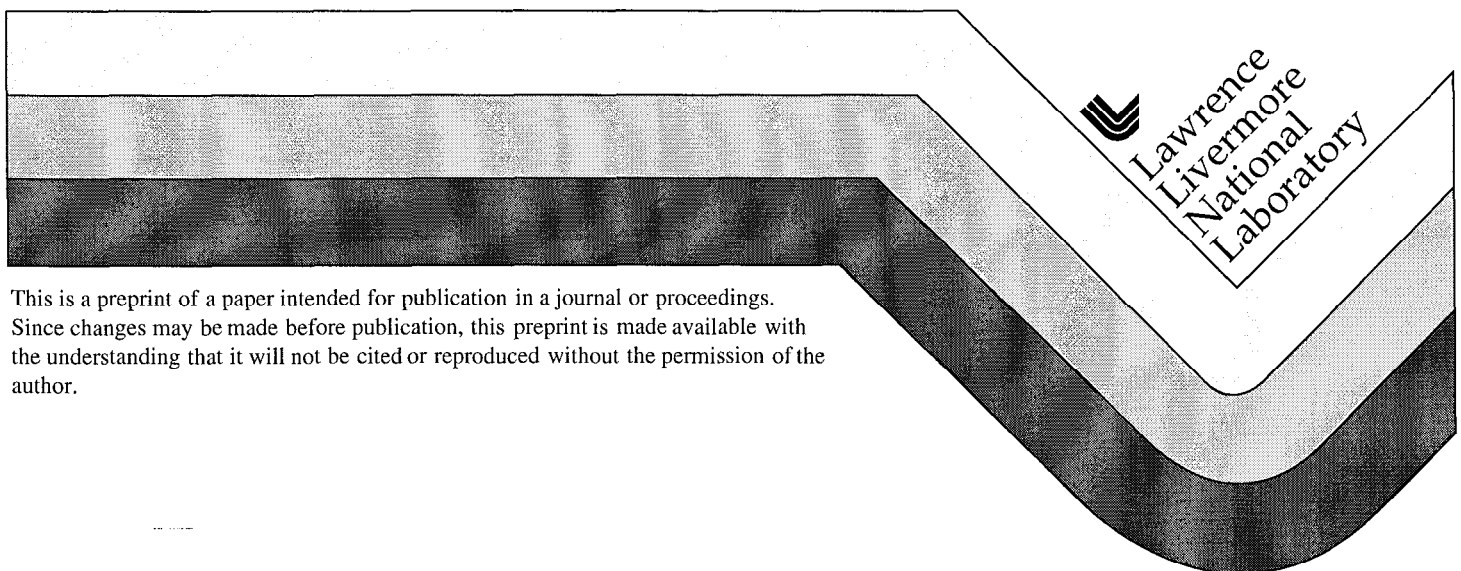# Laser Impingement on Bare and Encased High Explosives: Safety Limits

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Laser Impingement on Bare and Encased High Explosives: Safety Limits

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ABSTRACT

During the course of experiments involving high explosives, (HE), alignment lasers are often employed where the laser beam impinges upon a metal encased HE sample or on the bare HE itself during manned operations. While most alignment lasers are of low enough power so as not to be of concern, safety questions arise when considering the maximum credible power output of the laser in a failure mode, or when multiple laser spots are focused onto the experiment simultaneously. Safety questions also arise when the focused laser spot size becomes very small, on the order of 100 μm or less.

This paper will address these concerns by describing a methodology for determining safety margins for laser impingement on metal encased HE as well as one for bare HE. A variety of explosives encased in Al, Cu, Ta and stainless steel were tested using the first of these techniques. Additional experiments were performed using the second method where the laser beam was focused directly on eight different samples of pressed-powder HE.

1. INTRODUCTION

Lasers are commonly used in experiments involving high explosives (HE). During the setup phase of the experiments alignment lasers are often used to precisely locate optical measurements on the sample surface. The alignment laser sometimes consists of a high-power laser that will be used later in the experiment during detonation but is operated at a much-reduced power for alignment purposes. The most common modes of operation with these lasers are when the laser beam impinges upon an explosive encased in a metal and when the beam impinges directly upon the explosive's surface.

Laser Impingement on Bare and Encased High Explosives: Safety Limits

Most of the lasers operated in the alignment mode are of low enough power so as not to be of concern to experimenters during manned operation. Safety questions arise, however, when multiple-laser spots are focused onto the experiment simultaneously and when the laser spot size becomes very small, on the order of 100 μm or less. Additional concerns arise when a high-power laser is being used in an attenuated mode for alignment purposes. One must look at the maximum credible power that could reach the sample in a failure mode of the laser or the attenuation mechanism.

Calculations can be performed to estimate the maximum laser power that will cause a reaction and indeed, calculations should play a significant part in determining the safe level of operation. Calculations, however, should be verified by experiment before they are relied upon for safety purposes. Once a set of calculations have been experimentally verified then one might consider using such calculations to estimate power levels in new situations that have not been experimentally measured, but only if a strict set of calculational parameters are used pertaining to the new situation and the relationship of these parameters to safety considerations have been included in the previous experimental verification.

A methodology and philosophy of measurement need be established to make meaningful measurements to establish safety limits when working in manned operations where laser beams are impinging upon cased and bare explosives. One such method we have used at Lawrence Livermore National Laboratory (LLNL) is described in this paper.

2. ENCASED EXPLOSIVES

2.1. EXPERIMENTAL

When the HE is encased in metal the only credible way for the CW alignment laser to create a problem is by heating the metal to a temperature that could cause a reaction to begin in the HE. The most thermally sensitive of the common explosives we use at LLNL, PETN, does not show significant exothermic reaction below a temperature of 150 C. By determining what laser and experimental parameters will produce temperatures of this order on the surface of the metal in contact with the HE we can establish a set of safe and practical guidelines.

To simplify the experiments one need not even use HE as long as a material that simulates its thermal conductivity is placed on the back surface of the metal under test. These experiments explore the temperature rise of the surface of a metal plate opposite the laser irradiation as a function of incident laser power, laser spot size, type of metal and the thickness of the metal.

The experimental arrangement is shown in figure 1. A 7.62 x 7.62 cm square of metal was clamped to an aluminum holder which served as a heat sink for the experiment. The distance from the irradiated spot to the holder was 3.5 cm. A 1.0 cm thick piece of Styrofoam was epoxied to the back of the metal to simulate the worst case thermal conductivity of typical explosives. A type K thermocouple junction was placed on the back surface of the metal, under the Styrofoam, directly behind the position of the irradiated spot which is on the opposite surface of the metal. A small dab of vacuum grease was placed on the thermocouple junction-metal interface to aid in the thermal contact. The junction itself was 1.0 mm in diameter.

Laser Impingement on Bare and Encased High Explosives: Safety Limits

The procedure used was to first use very low laser power to align the beam spot on the target metal. Next the sample holder was removed and a Coherent Beamcode analyzer was put in its place to measure the spot size. This step can be repeated for various sample positions along the railing and the railing position marked for various spot sizes. The beam diameters were measured at full width, 10% maximum. The Beamcode detector was then removed allowing the beam to be collected by a Coherent 210 power meter. The laser power was then adjusted to the desired level. The laser was shuttered and the sample holder put back into place. The shutter is then opened and temperature readings are taken for the proscribed amount of time.

The laser used in these experiments was a Spectra Physics Millenia X, 532 nm cw laser. The laser is capable of an output of 11 W which translates to about 8.6 W maximum on the samples due to loss in turning mirrors and lenses.

With so many variables to consider, the strategy was to map the parameter space in a way that could identify the important dependencies without measuring every combination possible.

2.2. EXPERIMENTAL RESULTS

The dependence explored was that of temperature on the incident laser power. The sample for this experiment was a 0.254 mm thick piece of OFHC copper. The laser spot size was 0.5 mm diameter. Figure 2 shows the results plotted as a function of time. The samples took about 10 to 12 minutes to reach an approximate equilibrium value.

A plot of the equilibrium temperature reached for each power level as a function of the input laser power (figure 3) gives a linear relationship.

The next experiment looked at the effect of the metal composition on equilibrium temperature. The samples were 0.0254 cm thick squares of copper, aluminum, tantalum and stainless steel. The laser spot size for these measurements was 0.1 mm and the incident laser power was 4 W. The results of these measurements can be seen in figure 4. The equilibrium temperature should be, to first order, proportional to the inverse of the product of the thermal conductivity and the reflectivity of the target material:

$$T \propto 1/K*R \tag{1}$$

where K is the thermal conductivity of the metal and R is the reflectivity at 532 nm. Figure 4 also shows a normalized curve calculated from (1). To first order the data can be explained by (1, which assumes a one-dimensional heat flow, ignores air convection and radiation. These higher order effects will tend to bring the calculated values for Ta and SS down and would make for a better agreement than shown.

Stainless steel was used to investigate the dependence of equilibrium temperature values with power density of the laser beam because the temperature rise is most pronounced of all the metals we tested. The stainless steel was once again 0.0254 cm thick. There are two ways one can approach this problem. First, the laser spot size was varied keeping the laser power density constant. Figure 5 is a plot of the equilibrium temperature vs. spot size with a constant power density of 377 W/cm^2. This plot is merely a confirmation of the data we took on temperature vs. total input power. The spot size has little to do with equilibrium temperature values.

Laser Impingement on Bare and Encased High Explosives: Safety Limits

A second way to look at this is to vary the spot size and keep the total input power fixed. The results for three power levels on a 0.0254 cm thick stainless steel sample are shown in figure 6. In the range measured here from 188 W/ cm^2 to 50,000 W/ cm^2 the power density appears to have very little to do with the temperature rise.

The previous results require some discussion. In all of these experiments the thermocouple junction is larger than the laser spot size. Figure 7 shows some relative sizes involved in the measurements. Any spot smaller than the thermocouple junction should give approximately the same results for the same laser input power. The mechanism that allows this is the thermal conduction of the metal. The amount of heat conducted away from the area receiving the laser fluence is proportional to the temperature gradient. The same laser fluence on a smaller area will cause the temperature in the immediate area of the front surface to rise higher. This temperature increase in turn, causes a higher temperature gradient and, therefore, more heat to be conducted away from the area. There is a gradient front to back as well as the radial heat gradient on the plate. Because of the poor thermal conductivity of the Styrofoam (explosive) the heat flow in the radial direction will dominate. So we would expect the temperature distribution on the back surface of the plate to vary slowly over a diameter roughly equal to the thickness of the metal and then fall off more rapidly. At any rate, the peak temperature in the temperature distribution curve cannot be much more than a factor of two higher than the average we measure if any credible physical distribution of the energy is considered.

For spot sizes larger than the thermocouple junction, some of the energy will be deposited in the area outside the contact the junction makes with the metal surface. We would expect to see a variation with spot size in this case, but the temperatures are so low that they will be of little interest in this study.

The last set of measurements involved looking at the dependence of the equilibrium temperature on the thickness of the metal sample. Again the first experiment used stainless steel with a .1 mm spot size and 1 W of laser power. Sample thickness of the stainless varied from .254 mm to .889 mm (figure 8). As one would expect the temperature decreases as the thickness increases. At larger thickness the temperature should asymptotically approach ambient and for smaller thickness one might expect a deviation to larger temperature values. This is indeed the case as shown in figure 9 where measurements were made on Al ranging from 0.0127 mm to 1 mm.

3. BARE EXPLOSIVES

3.1. EXPERIMENTAL

In these experiments 532 nm laser light (with the exception of the HMX sample where we used 514 nm light) was focused directly on the surface of eight common pressed-powder explosives. Samples measured were PETN, HMX, LX-16 (96%PETN/4% FPC 461 binder), LX-14 (95.5% HMX/4.5% Estane), LX-15 (95% HNS/5% Kel-F), LX-17 (92.5% TATB/7.5% Kel-F), PBX-9407 (94% RDX/6% Exon 461), and pressed TNT. Spot sizes were again measured with the Coherent Beamcode analyzer and for most experiments were 1 mm diameter. The tests were done inside a 2-gm-rated explosive chamber and the laser power level inside the chamber was measured before each experiment with the Coherent 210 poser meter.

Laser Impingement on Bare and Encased High Explosives: Safety Limits

The explosive samples were held in a plastic sleeve which was inserted in a Delrin holder. The Delrin holder was placed in a stainless steel holder inside the chamber. Heat flow had to go through several millimeters of plastic/Delrin to reach the metal heat sink, so the HE was fairly well thermally isolated. The sample size was 6.35 mm in diameter and 2 mm thick with the exception of the PETN sample which was 7.62 mm in diameter and 7.62 mm thick. Another difference with the PETN was that it was held in an aluminum holder.

All samples were irradiated for twenty minutes with one exception to be discussed later. The samples were inspected under a microscope both before and after irradiation. The criteria for damage/no damage was the visual inspection.

3.2. EXPERIMENTAL RESULTS

Table 1 summarizes the power levels where damage, if any, was observed for the various samples. The "pure white" samples were very difficult to damage. This is probably due to the very high albedo (~80%) and the high transmission and scattering of the laser light inside the sample. The energy simply is not concentrated enough to cause a problem. A dramatic example of the difference between a highly scattering and a more absorbing surface is that of the LX-14 sample. In LX-14 some of the molding powder granules are dyed blue for identification purposes, leaving a white and blue mottled coloring. When the white area of the sample was irradiated no damage was observed at 800 mW. However, when the laser light was focused onto the blue dye areas the same amount of incident power burned a hole completely through the sample. Laser power had to be dropped to 340 mW on the dye-colored areas before the damage threshold was reached.

The LX-16 sample (PETN + 4% FPC 461 binder) showed no damage at 800 mW with a 1 mm spot size but at .5 mm spot size a small area on the surface looked "glassy" with tiny fracture lines radiating outward. The surface was probably starting to melt and upon removal of the beam the area underwent rapid cooling and stress fractures were formed. It is interesting that pure PETN did not show damage at these levels whereas the LX-16 did. This is most probably due to the binder in the LX-16. Note that the power density levels we are dealing with are 100 W/cm^2 for a 1 mm spot size and 400 W/cm^2 for the .5 mm spot size.

The LX-17 (figure 10) and LX-15 samples showed the formation of crystals around the damage sites. This suggests that vaporization occurred at the damage sites and the crystals formed in condensation. This also suggests that it is very difficult to initiate these materials with laser light. To emphasize this point 1.05 W was focused onto a 0.172 mm diameter spot on a sample of LX-15. This is 4500 W/cm^2. After nine minutes, the sample showed a large, cone-shaped crater with a 1 cm column of ash snaking from the damage site. It did not detonate. If, however, the sample had been confined an explosion is a possibility.

4. DISCUSSION AND SUMMARY

We have chosen a conservative approach for the amount of laser light allowed on explosive assemblies during manned operations. The data from section 1 for encased explosives allow us to set some limits based

Laser Impingement on Bare and Encased High Explosives: Safety Limits

upon safety margins deemed acceptable. For a 50 °C maximum temperature allowed for the explosive during laser irradiation (~30 °C above ambient), and for a .25 mm thick sample of the metals the following input laser power levels can be determined:

Cu	4.0 W
Al	5.0 W
Ta	0.7 W
SS	0.23 W

Note that these levels have an additional factor-of-two safety margin to account for any possible temperature distribution within the thermocouple junction area. The 50 °C limit is a factor of about 4 below the temperature at which PETN, the most thermally sensitive of the common explosives we used, shows some sign of reaction.

As a further safety margin, let's assume that we have a blackened area of the metal that will cause a total absorption of the laser energy. Using the values of the reflectivity in figure 11[1,2,3] we can adjust the safety margins downward for a totally absorbing material:

Cu	1.32 W
Al	0.35 W
Ta	0.34 W
SS	0.10 W

Most alignment intensities at LLNL are no more than 5 mW. There is occasion, however, when we desire to put multiple alignment beams on the explosive assembly. Assume we have 20 beams, each with a power of 5 mW, all concentrated onto a .2 mm diameter footprint. This worse case scenario then would have a total power of .1 W on the metal. This is the value for stainless steel that would cause a 50 °C temperature on the metal in the case of a totally absorbing area. Even though this scenario is unlikely we have determined that it has an unacceptable safety margin. If we limited the number of simultaneous beams to 5 this would buy us another factor of 4 in safety. Combined with the fact that or original temperature rise is a factor of 4 or more below the most thermally sensitive explosive we deal with, we now in reality have a factor of 16 safety margin for a worse case scenario.

Even though the majority of the data taken is at 532 nm, figure 11 shows that in the case of the four metals considered above the curves are relatively flat or improve toward longer wavelengths in the range of 500 to 800 nm. This information, combined with the fact we have already taken a worse-case scenario where all of the laser energy is absorbed, there is no reason that any laser in this range could not safely be used under the above restrictions.

In the case of laser power on bare HE the worst case measured was PBX-9407 which showed no damage at 40 mW and only very slight damage at 75 mW. If we again take a conservative approach we can set a limit of 7 mW of laser power on bare HE **for those explosives measured and at the measured wavelengths.** This level is roughly a factor of ten below the level at which damage was first observed for the worst-case explosive measured. Different explosives may have radically different absorbing characteristics and different wavelengths may be absorbed more strongly than 532 or 514 nm Therefore the data on the bare explosives

measured should only be used as a rough guideline for setting limits of laser power on bare explosives during manned operations. **Any new explosive or any operation using laser power at a different wavelength should be measured in an environment where the explosive is safely contained before allowing manned operations.**

5. RECOMMENDATIONS

The following recommendations were made at LLNL for manned operations involving laser power impinging upon high explosives:

- Alignment laser power shall be limited to ≤ 5 mW/spot when multiple-beam laser light is incident upon cased explosives.

- The spot size of the laser beam on the metal casing shall be limited to ≥ 0.2 mm.

- The thickness of the metal plate shall be ≥ 0.25 mm

- The number of spots allowed to be illuminated at one time shall be ≤ 20 for Al, Cu and Ta but shall be limited to 5 for SS. The only materials approved for use with the above limitations are: Cu, Al, Ta and stainless steel. All other metals shall be limited to one spot.

- The wavelength of the laser used be limited to the range from 500 nm to 800 nm.

- When a single laser beam is incident upon cased explosives the power level shall be limited to ≤ 25 mW with the spot size ≥ .2 mm and the metal thickness ≥ 0.25 mm for Al, Cu, Ta and SS. All other metals must be measured and a peer review take place for power levels > 5 mW and ≤ 25 mW.

- The power shall be limited to ≤ 7 mW for a laser beam of 532 nm on the bare explosives listed in table 1. All other explosives must be measured at the laser wavelength to be used and a peer review take place before manned operations are allowed.

We believe these recommendations are safe and yet allow most alignment operations to take place without undue limitations. The recommendations are conservative but practical. Safety must always be the first concern when dealing with high explosives.

Laser Impingement on Bare and Encased High Explosives: Safety Limits

LIST OF REFERENCES

4. American Institute of Physics Handbook, 3rd edition.
5. The Infrared Handbook, editors Wolfe and Zizziz, 1978.
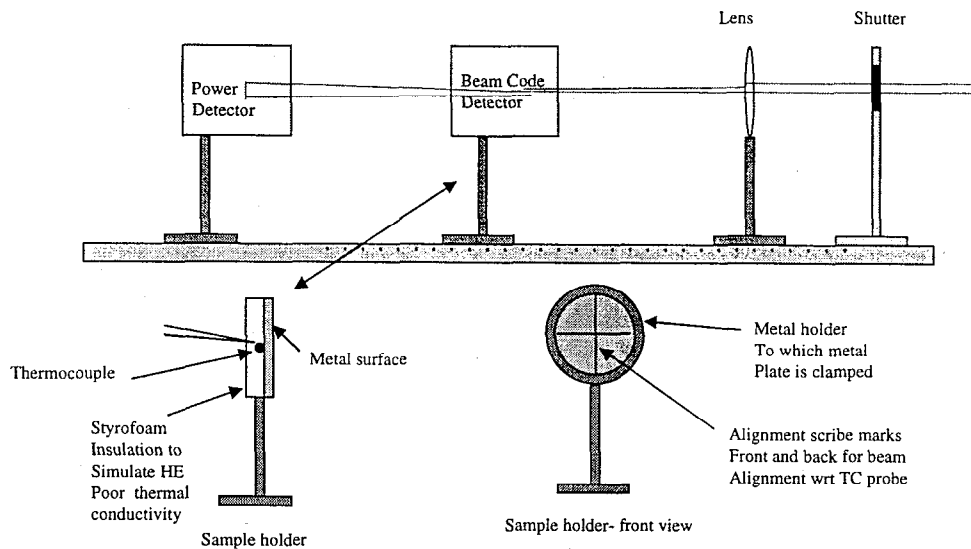6. Physics Data, Optical Properties of Metals, Nr. 18-2, 1981.

figure 1. Experimental arrangement for measuring laser-induced temperature changes on metal plates.

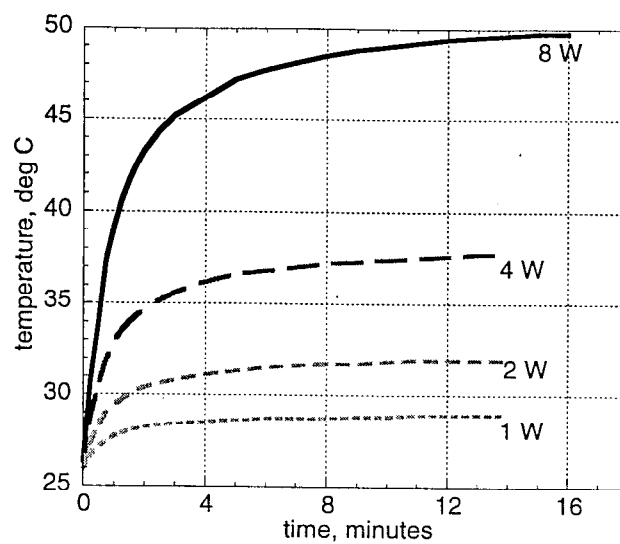# Laser Impingement on Bare and Encased High Explosives: Safety Limits

figure 2. Temperature vs. laser power , 0.254 mm Cu, 0.5 mm laser spot size

$$y = 25.917 + 2.9687x \quad R = 0.99998$$
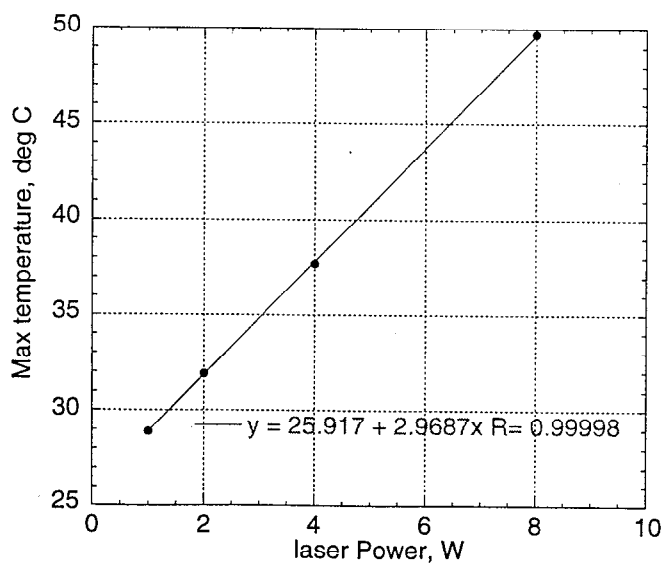
Figure 3. Equilibrium temperature vs. laser input power for 0.254 mm Cu, 0.5 mm spot size.

Laser Impingement on Bare and Encased High Explosives: Safety Limits
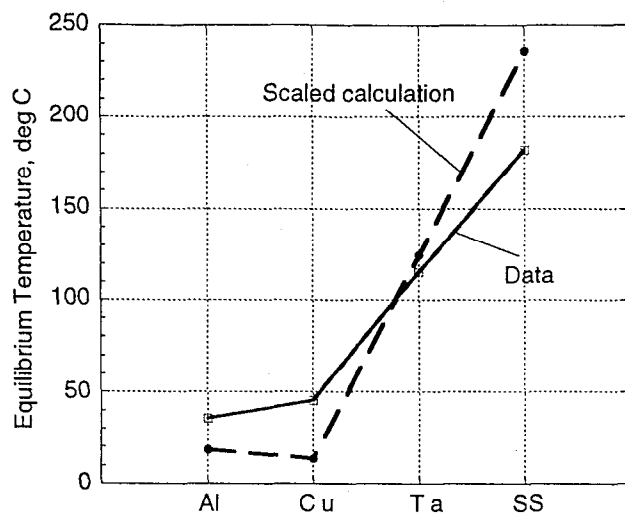
Figure 4. Equilibrium temperature vs. metal type. Laser power was 4 W and laser spot size was 0.1 mm. Also shown is a scaled value for each material derived from equation 1.
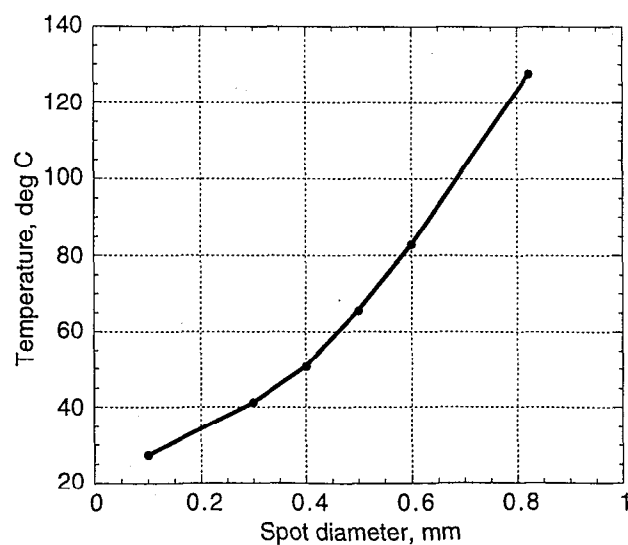
Figure 5. Equilibrium temperature vs. spot size at constant Power density of 377 W/cm^2. Metal is 0.254 mm thick SS.

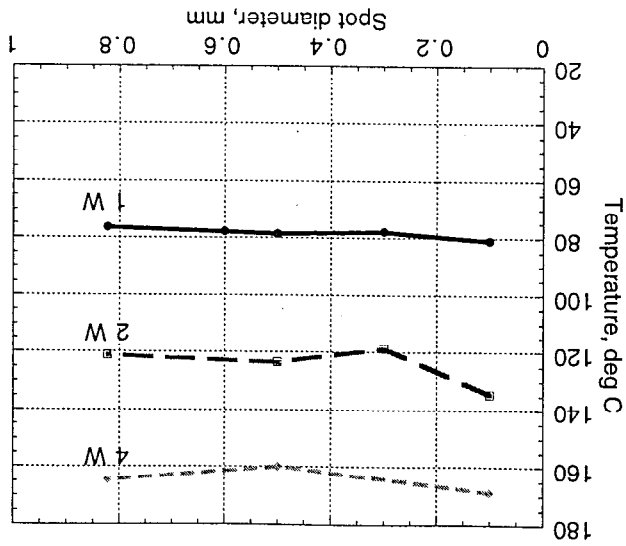# Laser Impingement on Bare and Encased High Explosives: Safety Limits

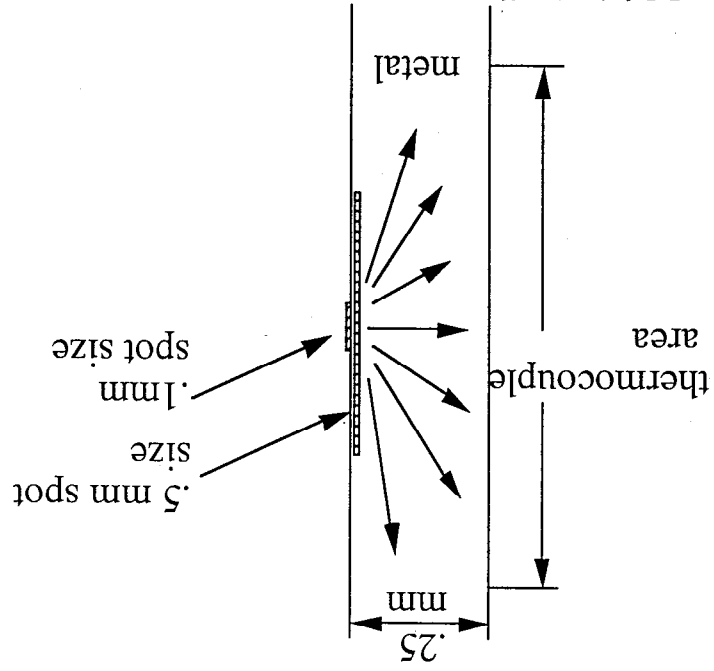*Figure 6. Equilibrium temperature vs. spot size at several input power levels.*

Figure 7. Relative size of laser spots with respect to the thermocouple junction area.

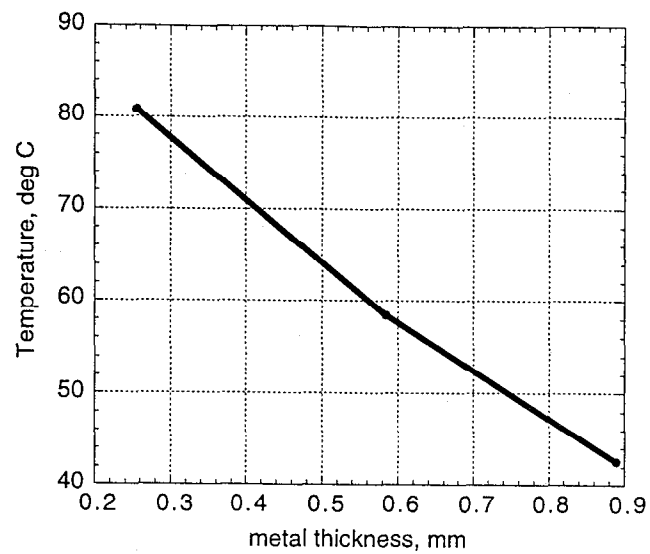# Laser Impingement on Bare and Encased High Explosives: Safety Limits

Figure 8. Equilibrium temperature vs. SS thickness for 1 W incident laser power and a 0.1 mm spot size.
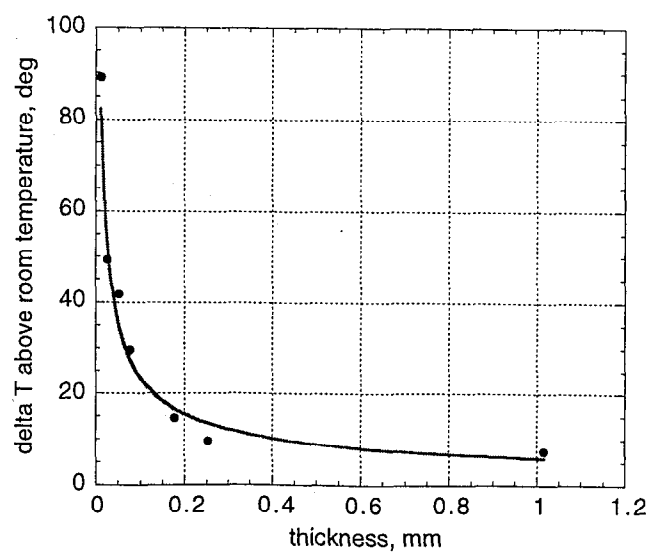

Figure 9. Increase in temperature above ambient for AL vx. Thickness for 4W incident laser power and a .1 mm spot size.

Laser Impingement on Bare and Encased High Explosives: Safety Limits

HE	Damage Power level	Spot size	Comments
PETN	No damage at 800 mW	1 mm, .5 mm	density = 1.55 gm/cc
HMX	No damage at 654 mW	.3mm	514 nm laser
LX-16	800 mW	1 mm, .5 mm	1 mm no damage, .5 mm showed damage
LX-14	340 mW (+0, -50 mW)	1 mm	damage level for blue dye area
TNT	300 mW (+10, -50 mW)	1 mm	
LX-17	230 mW (+0, -50 mW)	1 mm	
LX-15	110 mW (+0, -30 mW)	1 mm	
PBX-9407	70 mW (+0, -25 mW)	1 mm	

Table 1. Damage Thresholds measured for eight explosives for laser power directly on the bare HE.

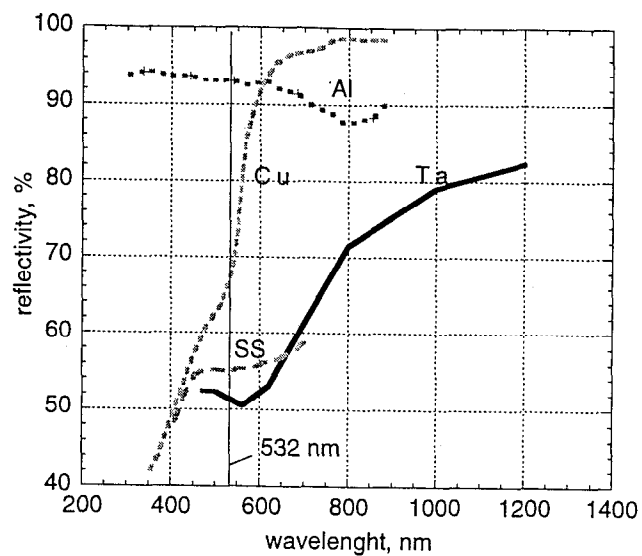*Figure 10. LX-17 damage after laser irradiation with 800 mW and a 1.0 mm spot size.*

Figure 11. Reflectivity vs. wavelength for the metals used in these experiments.

Laser Impingement on Bare and Encased High Explosives: Safety Limits